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THE FLOW OF PLASMA IN THE SOLAR TERRESTRIAL ENVIRONMENT

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SPTP Accomplishments

In association with our most recent NASA Theory Program, we have written 40 scientific papers and we have made 41 scientific presentations at both national and international meetings. Lists of the NASA Theory personnel, publications, and presentations are attached. In the paragraphs that follow, we outline the scientific goals of our program and then briefly highlight some of the papers we have submitted for publication within the last six months.

Scientific Goals

It has been clearly established, both experimentally and theoretically, that the various regions of the solar-terrestrial system are *strongly coupled*, that the coupling processes exhibit *time delays*, and that *feedback mechanisms* exist. For example, changes in the solar wind dynamic pressure and the interplanetary magnetic field affect the magnetospheric currents and electric fields, which, in turn, affect the ionospheric convection pattern, electron density morphology, and ion composition at high latitudes. The changes in the ionosphere then affect the thermospheric structure, circulation and temperature on a global scale. The changes in the ionosphere-thermosphere system then act to modify the magnetospheric processes. The variations in the ionospheric conductivities modify the magnetospheric electric fields and the large-scale current system linking the two regions. Additional feedback mechanisms occur in the polar cap via the 'polar wind' and in the auroral zone via 'energetic ion outflow,' and these ionospheric ions are a significant source of mass, momentum and energy for the magnetosphere. However, all of the coupling and feedback mechanisms have time delays associated with them, which further complicates the situation.

With the above description in mind, the overall goal of our NASA Theory Program is to study the *coupling, time delays,* and *feedback mechanisms* between the various regions of the solar-terrestrial system in a *self-consistent, quantitative* manner. To accomplish this goal, it will eventually be necessary to have time-dependent macroscopic models of the different regions of the solar-terrestrial system and we are continually working toward this goal. However, our immediate emphasis is on the near-earth plasma environment, including the ionosphere, the plasmasphere, and the polar wind. In this area, we have developed *unique global models* that allow us to study the coupling between the different regions.

Another important aspect of our NASA Theory Program concerns the effect that localized 'structure' has on the macroscopic flow in the ionosphere, plasmasphere, thermosphere, and polar wind. The localized structure can be created by structured magnetospheric inputs (i.e., structured plasma convection, particle precipitation or Birkeland current patterns) or time variations in these inputs due to storms and substorms. Also, some of the plasma flows that we predict with our macroscopic models may be unstable, and another one of our goals is to examine the stability of our predicted flows.

Because time-dependent, three-dimensional numerical models of the solar-terrestrial environment generally require extensive computer resources, they are usually based on

relatively simple mathematical formulations (i.e., simple MHD or hydrodynamic formulations). Therefore, another long-range goal of our NASA Theory Program is to study the conditions under which various mathematical formulations can be applied to specific solar-terrestrial regions. This may involve a detailed comparison of kinetic, semi-kinetic, and hydrodynamic predictions for a given polar wind scenario or it may involve the comparison of a small-scale particle-in-cell (PIC) simulation of a plasma expansion event with a similar macroscopic expansion event. The different mathematical formulations have different strengths and weaknesses and a careful comparison of model predictions for similar geophysical situations will provide insight into when the various models can be used with confidence.

Ionospheric Dynamics and Energetics

The terrestrial ionosphere at high latitudes is strongly affected by convection electric fields, particle precipitation, field-aligned currents, and downward heat flows. Over the years, we have conducted numerous studies of the effects that these processes have on the ionosphere, with the emphasis on large-scale ionospheric features. More recently, our focus has shifted toward studying the effect that mesoscale structures (blobs, patches, auroral arcs, etc.) have on the ionosphere. In general, these studies were conducted using our time-dependent, 3-dimensional, high-resolution, multi-ion ionospheric model. With this model, the density distributions for six ion species (NO^+, O_2^+, N_2^+, N^+, O^+, He^+) and T_e and T_i are obtained from a numerical solution of appropriate continuity momentum and energy equations over the altitude range from 90 to 1000 km.

During the last six months, our ionospheric model was used in a comprehensive parametric study of the ionospheric modifications associated with sun-aligned polar cap arcs (paper 29). The key arc parameters were systematically varied, including the width, the electric field structure, and the precipitation energy flux and characteristic energy. The main conclusions of our study are that the ionospheric response to arcs is nonlinear, with the largest modifications occurring for intermediate arc widths and electric field strengths, and that the *E* and *F* region responses are very different. Additionally, we found that as the ionospheric plasma drifts into, across, and then out of a sun-aligned arc, it is modified in a nonuniform manner in response to the production and heating in the arc (Figure 1). The ionospheric modification is characterized by enhanced *E*-region densities within the precipitation region, enhanced *F*-region densities due to production from the soft component of precipitation and to upward diffusion from the lower ionosphere, and enhanced topside densities due to increased scale heights associated with the ion and electron heating in the arc. As the flux tube convects out of the arc, the *E*-region densities decrease rapidly due to the fast recombination of the molecular ions. However, the *F*-region density actually increases as the flux tube first leaves the arc due to downward diffusion from the topside ionosphere, which is in response to the decrease in T_e and T_i. Subsequently, the *F*-region density decays slowly due to the relatively slow O^+ recombination rate. This produces the distinctive '*candle flame in the wind*' in the color plot of N_e, with cross arc convection corresponding to the wind.

Ionosphere – Magnetosphere Coupling → Electrodynamics of Polar Cap Arcs

It is well known that the electric fields, particle precipitation, auroral conductivity enhancements, and Birkeland currents that couple the magnetosphere-ionosphere system

are strongly dependent upon the direction of the interplanetary magnetic field (IMF). When the IMF is southward, the Birkeland currents flow in the Region 1 and 2 current sheets, the *F* region plasma convection exhibits a 2-cell structure with anti-sunward flow over the polar cap, and the auroral electron precipitation and ionospheric conductivity enhancements are confined to the statistical auroral oval. For this situation, empirical (statistical) models have been developed to describe the important magnetospheric parameters (field-aligned currents, electric fields, etc.) and these models have been used successfully to model ionospheric and thermospheric processes. In general, however, magnetospheric electric fields and particle precipitation exhibit a considerable amount of spatial (mesoscale) structure and this could have a significant effect on the ionosphere-thermosphere system. The structure is particularly evident during northward IMF, when multiple sun-aligned arcs can occur in the polar cap. Unfortunately, the convection electric field characteristics in and near sun-aligned arcs have not been fully elucidated and, hence, it is currently not possible to rigorously model the ionosphere-thermosphere coupling when sun-aligned arcs are present. In an effort to address this issue, a two-dimensional, time-dependent model of polar cap arcs was developed at USU in which the electrodynamics of the polar cap arc is treated self-consistently in the frame of the coupled magnetosphere-ionosphere (M-I) system (paper 30).

During the last six months, we used our electrodynamic model of polar cap arcs to study the effect of an inhomogeneous ionosphere on Alfvén wave reflection. In the model, magnetospheric shear flow is imposed and an Alfvén wave is then triggered, which propagates toward the ionosphere. Initially, the ionosphere is characterized by simple background conductivity and convection patterns. The downward propagating Alfvén wave can be partially reflected from the ionosphere and can bounce back and forth between the ionosphere and magnetosphere. Also, the upward field-aligned current associated with the Alfvén wave enhances the ionospheric conductance and the conductance change excites a secondary Alfvén wave which propagates toward the magnetosphere. The new result we found is that an *initially inhomogeneous ionosphere* causes a *rotation* of the reflected Alfvén wave field, which in turn produces field-aligned currents that originate in the ionosphere. Our results indicate that a strong conductivity nonuniformity in the direction perpendicular to the incident wave field, a large Hall to Pedersen conductivity ratio, and low conductivity values lead to large rotations of the reflected wave field (by as much as 40°). These results explain the cross-flow that has been measured with respect to polar cap arcs. Specifically, the polar cap ionosphere is usually very inhomogeneous, and the electric fields associated with the magnetospheric shear flow typically are at an angle with respect to the background conductivity gradient in the polar cap. Therefore, the conditions are ideal for a rotation of the Alfvén wave electric field vector, which leads to an ExB drift across the polar cap arc. Based on our results, we predict that the flow across the polar cap arc should be stronger in winter than in summer, since higher conductivities lead to smaller rotations.

Ionosphere – Magnetosphere Coupling → Polar Wind

The 'classical' polar wind is an ambipolar outflow of thermal plasma from the terrestrial ionosphere at high latitudes. The outflow, which can consist of H^+, He^+, and O^+, begins at about 800 km. As the ionospheric ions flow up and out of the topside ionosphere along diverging geomagnetic field lines, they are accelerated and eventually

become supersonic (above about 1300 km). As part of our SPTP research, we are studying several aspects of the polar wind, including its stability, 3-dimensional structure, outflow features during magnetic storms, and flow characteristics in the collision-dominated to collisionless transition region. We are also developing advanced time-dependent polar wind models. During the last six months, we concentrated on comparing the features predicted by our polar wind models with measurements (papers 22, 23, and 34).

In our model/measurement comparisons, we collaborated with scientists that operate the EISCAT incoherent scatter radar in order to study the vertical structure of the polar wind. In the first study (paper 22), the emphasis was on determining if the EISCAT-VHF radar was capable of providing information on the H^+ vertical velocity and density in the polar wind. A method to deduce the H^+ parameters was developed and it was then tested using 'synthetic' ionospheric profiles. Specifically, an 'ideal' ionosphere was first obtained by solving the continuity and momentum equations for H^+, O^+, and electrons over the altitude range 200-1400 km. Incoherent scatter spectra were then generated from this 'ideal' ionosphere, using the radar characteristics, and the spectra were analyzed in the standard way to obtain 'synthetic' O^+ and electron profiles. These profiles were subsequently used to deduce the H^+ parameters. Finally, the *'synthetic'* ionospheric profiles were compared with the known *'ideal'* ionosphere. From such an analysis it was concluded that the polar wind characteristics can be deduced from the EISCAT-VHF radar to altitudes as high at 1400 km.

In a companion paper (paper 23), the newly developed analysis procedure was used to investigate the topside O^+ and H^+ vertical ion flows above Tromsø on two nights; one very quiet and one moderately disturbed. In the third study (paper 34), a model/data comparison was conducted in order to elucidate the dynamic behavior of the topside ionosphere. Based on radar measurements of electric fields and field-aligned currents, a polar wind simulation was conducted to calculate the ionospheric response to momentum impulses from E-fields and currents, and the calculated response was compared with the radar measurements over the 300-1600 km altitude range. Figure 2 shows the simulation of the EISCAT observations. The perturbations associated with the adopted initial profiles disappear at about 21:00 UT and a quasi-steady state is achieved. At 22:00 UT, a strong electric field event occurs, and the subsequent O^+ frictional heating is clearly evident. In parallel, a perturbation propagates upward from the *F*2-region, which is most evident in the O^+ velocity. The electric field event lasts two hours (22-24 UT), but a field-aligned current event occurs at 23:00 UT. Its main effects are a strong electron heating and ion cooling. Simulations of this nature, in conjunction with incoherent scatter measurements, provide a powerful means of elucidating time-dependent polar wind characteristics and we expect to continue such comparisons.

Validity of Macroscopic Plasma Flow Models

Numerous mathematical formulations have been used over the years to describe plasma flows in the solar-terrestrial environment, including Monte Carlo, hybrid particle-in-cell (PIC), kinetic, semikinetic, hydromagnetic, generalized transport, and hydrodynamic formulations. All of these formulations have both strengths and limitations when applied to macroscopic plasma flows. For example, the transport formulations (hydromagnetic, generalized transport, and hydrodynamic) can describe multispecies flows, multistream flows, subsonic and supersonic flows, collision-dominated and collisionless regimes, chemically-reactive flows, and flows that are characterized by highly

non-Maxwellian conditions (generalized transport equations). Typically, these formulations can also be extended to multi-dimensions. They are limited, however, in that they are obtained by truncating the infinite hierarchy of moment equations and, in general, it is not clear how the truncation affects the solution. The kinetic and semikinetic models are particularly suited to collisionless, steady-state plasma flows. They have an advantage in that the full hierarchy of moment equations are implicit in the solution and multiple particle populations can be readily included. Some of their limitations are that they are difficult to apply to time-dependent, multi-dimensional or collisional flows and, as a consequence of the latter, an artificial discontinuity can occur at the boundary. Monte Carlo and PIC techniques have the advantage that you follow the motion of individual particles and, hence, a lot of the important physics can be included self-consistently. Monte Carlo techniques are particularly useful for collision-dominated gases, and with the PIC approach, self-consistent electric fields can be easily taken into account. Some disadvantages are that both techniques are computationally demanding and, therefore, they cannot be easily extended to multi-dimensional situations. Also, when PIC techniques are applied to macroscopic flows, "macroparticles" are used, and this introduces numerical noise, which can significantly affect the resulting physics. Specifically, the random scattering of particles due to numerical noise can significantly reduce temperature and heat flow anisotropies in an artificial manner.

In an effort to more fully elucidate the validity of the various plasma flow formulations, we systematically compared several of them for the same plasma flow conditions. The results of these studies were published in a series of papers that have been published during the last five years. During the last six months, we wrote a review article that summarized the various comparisons in order to put the work in perspective (paper 33). The review included comparisons of semikinetic, Monte Carlo, and generalized transport (Maxwellian based 13-moment and bi-Maxwellian based 16-moment) formulations. With regard to the geophysical conditions, comparisons were presented for the polar wind, the quiet solar wind, subsonic SAR-arc flows, and the escape of a minor neutral species. The flow features that were compared included the predicted densities, drift velocities, temperature anisotropies, heat flow asymmetries, and particle distribution functions. These comparisons have provided definitive conclusions about the strengths and limitations of the various mathematical formulations and have provided a guide as to when a given formulation can be applied in space physics.

Plasma Expansion Phenomena

We have continued our studies of plasma expansion phenomena because of their relevance to certain solar-terrestrial flows (solar wind, polar wind, interhemispheric flow, etc.). The problem is that rapid expansion of a plasma results in non-Maxwellian distribution functions, and consequently, superthermal tails, plasma instabilities, and wave-particle interactions may become important. Therefore, an understanding of the basic physics involved in a plasma expansion is necessary so that simplified, but reliable, macroscopic models can be developed for a range of solar-terrestrial applications.

In the past, we conducted *small-scale* numerical simulations in order to model plasma expansions *along* **B** using both 1-D (Vlasov-Poisson) and 2-D (PIC) codes. We also modelled *macroscopic* plasma expansions *along* **B** in order to compare the predictions obtained from the small-scale models with the macroscopic model. With support from our existing NASA Theory Program, we developed both a 2-D, height-integrated, cross-**B**, macroscopic plasma expansion model and a fully 3-D macroscopic plasma expansion

model (papers 2, 6, and 25). Our 3-D model has a unique capability for handling the large parallel-to-perpendicular conductivity ratio that exists in the ionosphere and is fairly general in that it can describe a range of plasma expansion scenarios, including the expansion of preionized clouds, plasma clouds that evolve from neutral gases, and plasma clouds that have 'initial' directional velocities at an angle to **B**.

During the last six months, we modified our 3-dimensional plasma cloud model so that it includes electrical coupling to a distant ionization layer (paper 39). The motivation for this work is connected with the propagation and decay of F-region plasma blobs. Measurements indicate that plasma blobs convect antisunward across the dark polar cap and then enter the nocturnal auroral oval. Our previous studies concerning the transport characteristics of pre-existing F-region blobs indicate that auroral electron precipitation usually does not destroy the blobs. However, small F-region blobs (<10 km) might diffuse across **B** and decay via electrical coupling to the E-region, a process not included in our global ionospheric model. Electrical coupling to the E-region is not expected to be important in the dark polar cap, where the E-region densities are low, but it might be important for blobs that convect into, and then remain in, the auroral oval where the E-region densities are high.

At the present time, the extension to our 3-D plasma cloud model is complete and several test runs have been conducted. The model maintains adequate resolution to describe the dynamics of an F-region plasma cloud and yet has sufficient resolution to properly describe the electrical coupling to the underlying E-region. In preliminary tests of the model, three cases were considered that covered different degrees of electrical coupling. Our results indicate that electrical coupling to a distant ionization layer does not affect the cloud expansion along **B**, but can have a major effect on the cross-**B** motion. The electrical coupling reduces the perturbation potential and perpendicular velocity of the cloud and delays the onset of plasma striations. As a result of the coupling, there is electron current between the F-region plasma cloud and the E-region, with an electron flow toward the cloud on one side and away from the cloud on the other side.

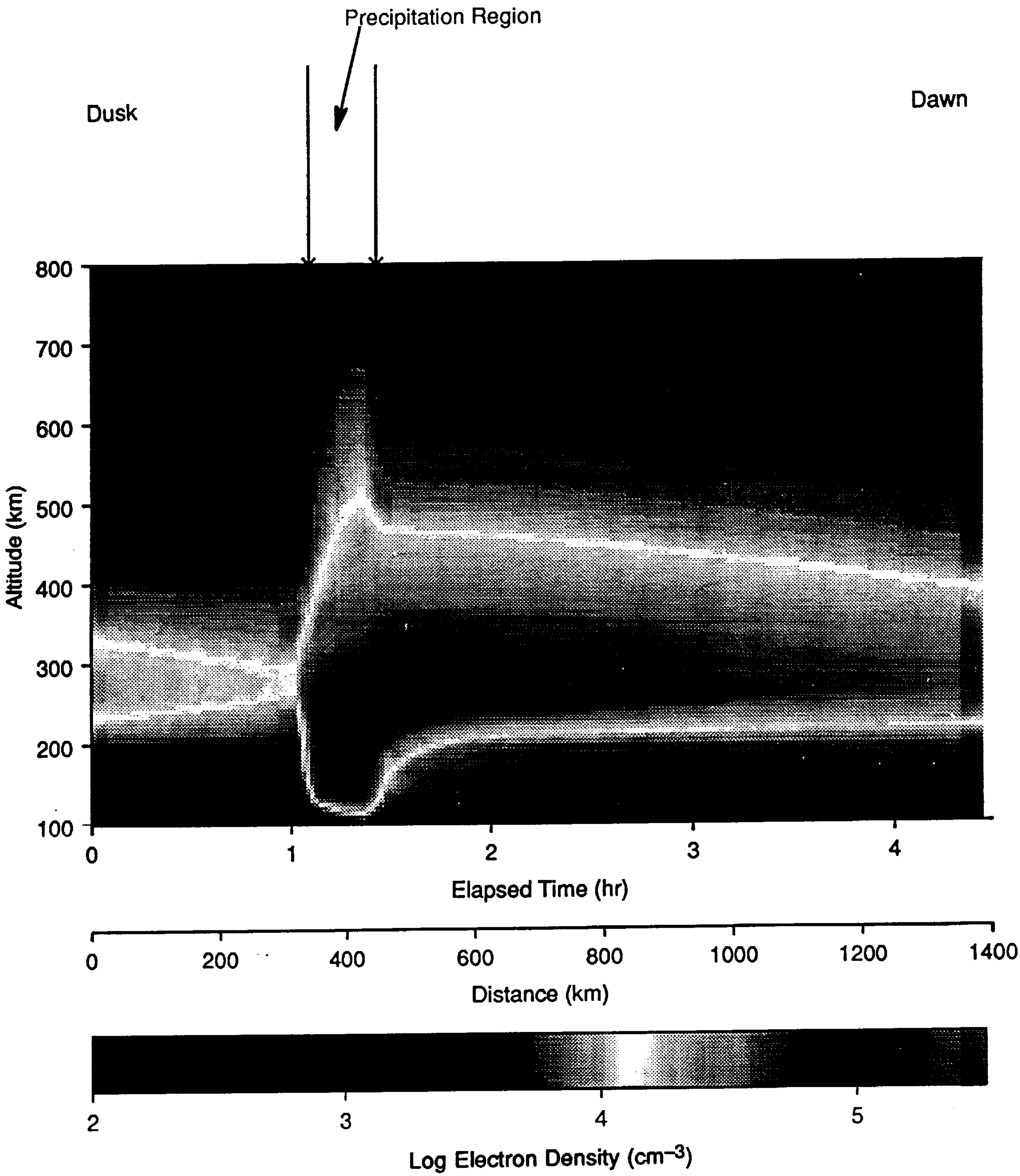

Figure 1. Contour plot of the N_e variation across a "phototype" sun-aligned arc. The flux tube convects from left to right across the arc (paper 29).

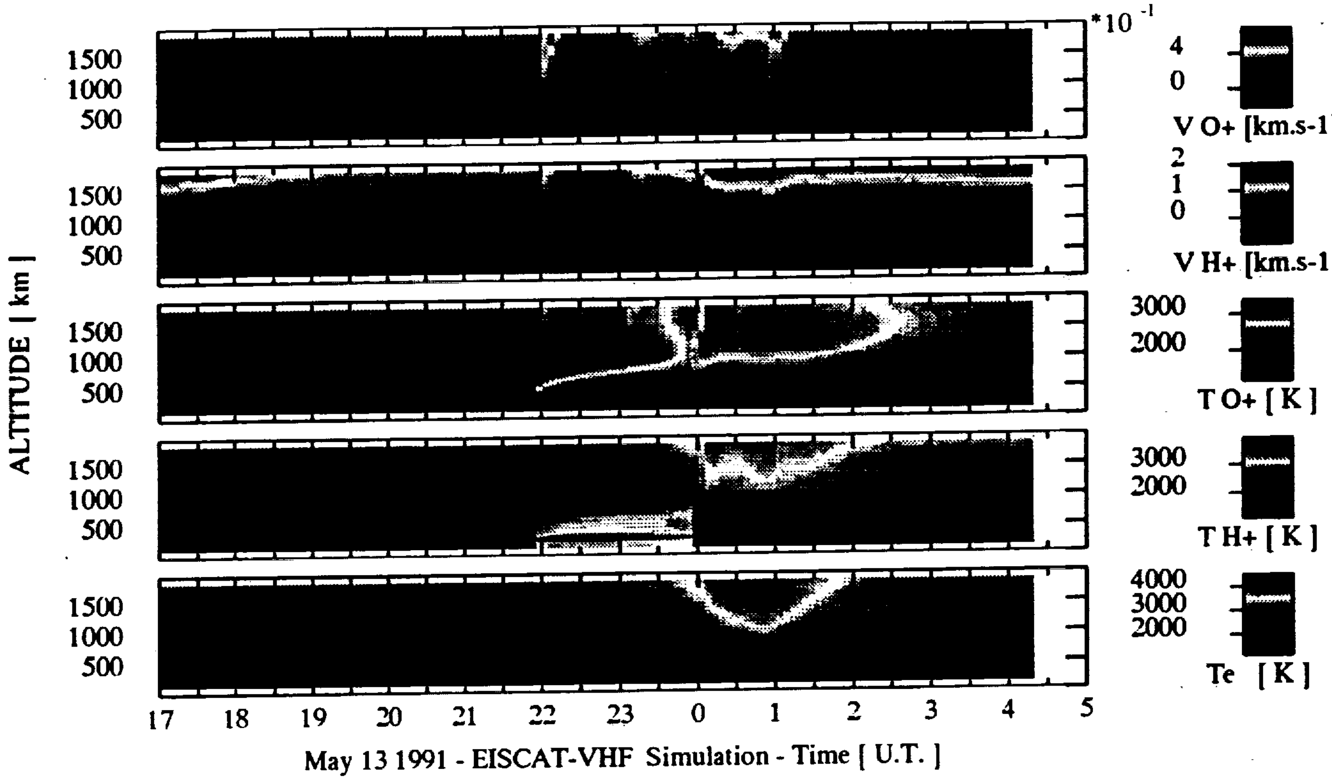

Figure 2. May 13, 1991, EISCAT-VHF simulation of the ionosphere. Shown in the panels are the O^+ and H^+ drift velocities and temperatures as a function of altitude and time (paper 34).

SPTP Personnel

Ph.D. Scientists

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